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Within the scope of conducted investigations it was proposed to define the active flow zone in one-dimensional models of unsteady open channel flow using the method, in which the division of the complex river channel cross-section is defined using interphase boundary of a specific roughness. The width of the active cross-section zone based on the detailed analyses of vegetation clusters in the flood plains was determined on the tested section of the River Warta. The mean width of the flood plain valley is 490 m and the width of the Warta channel ranges from 50 to 84 m. Flood plains are covered by tall grassy vegetation, clusters of shrubs and trees. During the passage of the flood wave in May and June 2010 a total of 16 probing measurements were taken using a StreamPro probe at cross-sections at 352.3 km, where a road bridge is located in Pyzdry. Additionally, two valley measurements were taken. Results of analyses were compared with the results of measurements with the application of an ADCP probe in the course of the flood in the year 2010. Results of velocity distribution measurements were referred to the results of hydraulic calculations, made using a 2D Rismo flow model. That model used the generated numerical model of the area. Additionally the model incorporated parameters of vegetation covering flood plains.

Keywords: active flow zone, ADCP probe, 2D flow model

1 Introduction

Wide flood plains have a significant effect on the transformation of bankful discharge and flood wave flow (*Laks et al.* 2013). In order to construct reliable, numerical models of unsteady open channel flows their effect has to be particularly taken into consideration (*Cunge* 1989). In models based on the system of Saint-Venant equations the effect of flood plains is included thanks to the identification in the computational cross-section of the river the area of the active cross-section and the area of cross-section dead zones - the so-called dead cross-section (*Maidment* 1992):). In such a computational system the basic problem is connected with the determination of the area of the active flow cross-section and a re-definition of model calibration parameters (*Abbott, Cunge* 1992). The range of the active zone depends on vegetation parameters and depth of water in flood plains.

2 Active flow zone

Within the scope of conducted investigations it was proposed to define the active flow zone in one-dimensional models of unsteady open channel flow using the Pasche method, in which the division of the complex river channel cross-section (Fig. 1) is defined using interphase boundary of a specific roughness (*Pasche* 1984). Taking into consideration the distribution of velocity presented Fig. 1 it was assumed that the active flow zone is composed of zones II and main channel. Having the width of main river channel we need to determine the width of zone II. Its range depends on the depth of water in flood plains and density of the vegetation structure. It is recommended to determine the width of the interaction area according to Pasche from the dependence:

$$b_{II} = \frac{c\,h_T}{\lambda_z\left(0.068e^{0.56C_T} - 0.056\right)} \tag{1}$$

where: λ_z – drag coefficient of flood plains [-], h_T – depth in the separation plane, *c* = 1.0 for flood plains and c = 1.7 for escarpments.

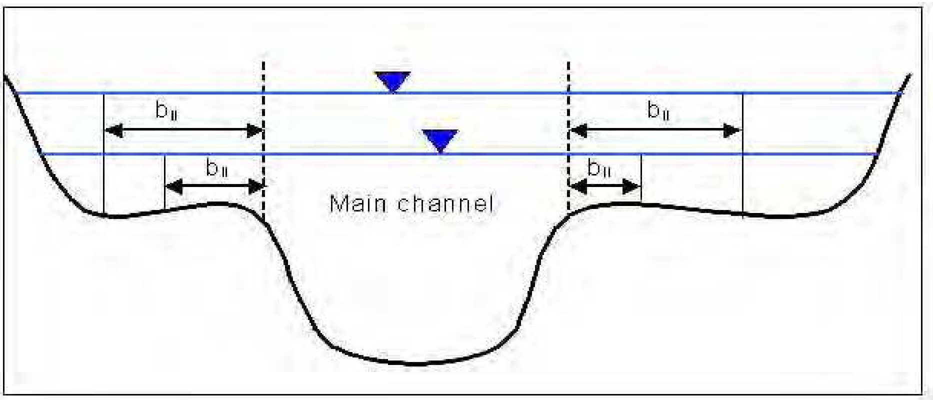

Figure 1: A contingent cross-section with specified activecross-section

Width of the active flow zone depends on the hydraulic radius of flood plains (depth), coefficient of roughness of flood plains and parameter C_T. The value of rubbing speed C_T according to Pasche was dependent on the parameter characterising vegetation structure at the river channel cross-section Ω :

$$C_T = -3.27\ \lg\Omega + 2.85 \quad (2)$$

Parameter Ω according to Pasche was dependent e.g. on the arrangement of trees, characterised by distances a_x, a_y and diameter d_p.

3 In-situ and model studies

Measurement during the 2010 flood on the Warta

The width of the active cross-section zone based on the detailed analyses of vegetation clusters in the flood plains was determined on the tested section of the River Warta. The modelled section is located between 351.82 km and 352.04 km. The mean width of the flood plain valley is 490 m and the width of the Warta channel ranges from 50 to 84 m. Flood plains are covered by tall grassy vegetation, clusters of shrubs and trees (Fig. 2a). During the passage of the flood wave in May and June 2010 a total of 16 probing measurements were taken using a StreamPro probe (Fig. 2b) at cross-sections at 352.3 km, where a road bridge is located in Pyzdry.

Additionally, two valley measurements were taken. Results of analyses were compared with the results of measurements with the application of an ADCP probe in the course of the flood in the year 2010.

Figure 2: a) A view of the flood plain valley of the Warta near Pyzdry during the 2010 flood, b) measurement of velocity distribution using a StreamPro probe during the 2010 flood on the Warta

StreamPro probe

StreamPro is a 2 MHz Acoustic Doppler Current Profiler (ADCP) designed for medium and small streams with depths up to 7 m (*Teledyne RD Instruments* 2008). The instrument has gained popularity in practical situations, as the majority of discharge measurements made by the USGS are in streams with mean depths of less than 1 m (*Fulford* 1992). The instrument can be operated using two deployment methods: moving-boat or stationary method (section-by-section).

The first method is implemented by slowly traversing the test area with an ADCP, from bank to bank. This method is most commonly used, because it is fast and efficient. The alternative section-by-section method is closer to the conventional discharge measurement protocol, whereby the instrument is successively positioned at several locations over the cross section to measure the velocities in verticals. Subsequently, the discharge is calculated using the velocity-area method applied to consecutive cross-section panels (i.e., spaces delimited by measured verticals). StreamPro ADCP discharge measurements using both approaches are popular (*Marsden* 2005, *Mueller and Wagner* 2009 and *Garcia et al.* 2012). These studies indicate that StreamPro ADCP displays a high variability in the measurement of velocities (*Gunawan et al.* 2010); however, the extensive USGS study conducted by *Rehmel* (2006) shows it is capable of measuring discharge.

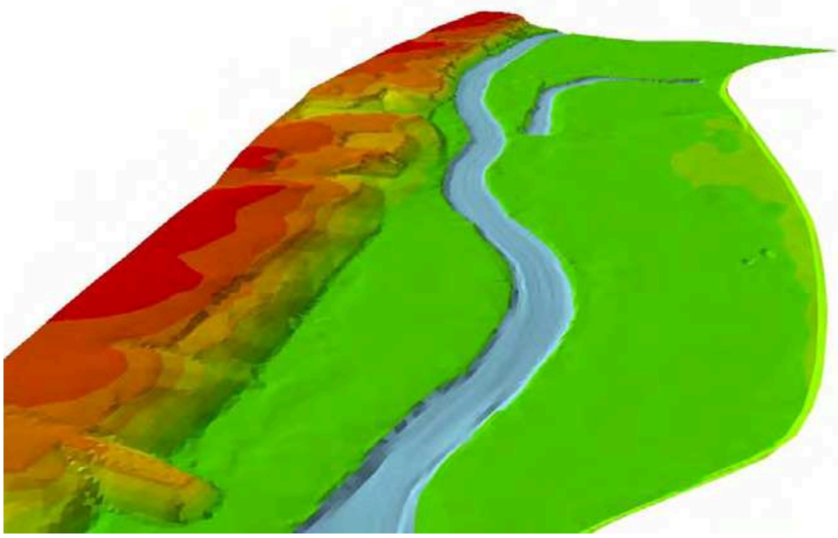

Figure 3: A 3D image of a section of the Warta above the road bridge in Pyzdry

Numerical model

Results of velocity distribution measurements were referred to the results of hydraulic calculations, made using a 2D Rismo (*Schröder* 1997) flow model („RIver Simulation MOdel“). That model used the generated numerical model of the area. Figure 3 presents a 3D image of the modelled section, generated in the ArcGIS application. Additionally the model incorporated parameters of vegetation covering flood plains. For grasses a supplementary sand roughness ks was adopted, while for trees and shrubs a supplementary diameter d_p and stem spacing a_x were determined. It was particularly essential to determine parameters of shrub structure.

4 Verification of results from the 2D model with in-situ measurements

A model of a fragment of a Warta river section was used in the simulation for flows measured during the passage of the flood wave in 2010. Calculations for the steady movement assumptions were realised for four flow variants (Q= 65 m^3/s, 165 m^3/s, 250 m^3/s and 385 m^3/s). Flow on the upper bank and the level on the bottom bank were assumed as boundary conditions. Additionally two control cross-sections inside the area were used to determine the accuracy of the settlement of balance of the equation of continuity. Figure 4 presents diagrams of locations of bank and control cross-sections.

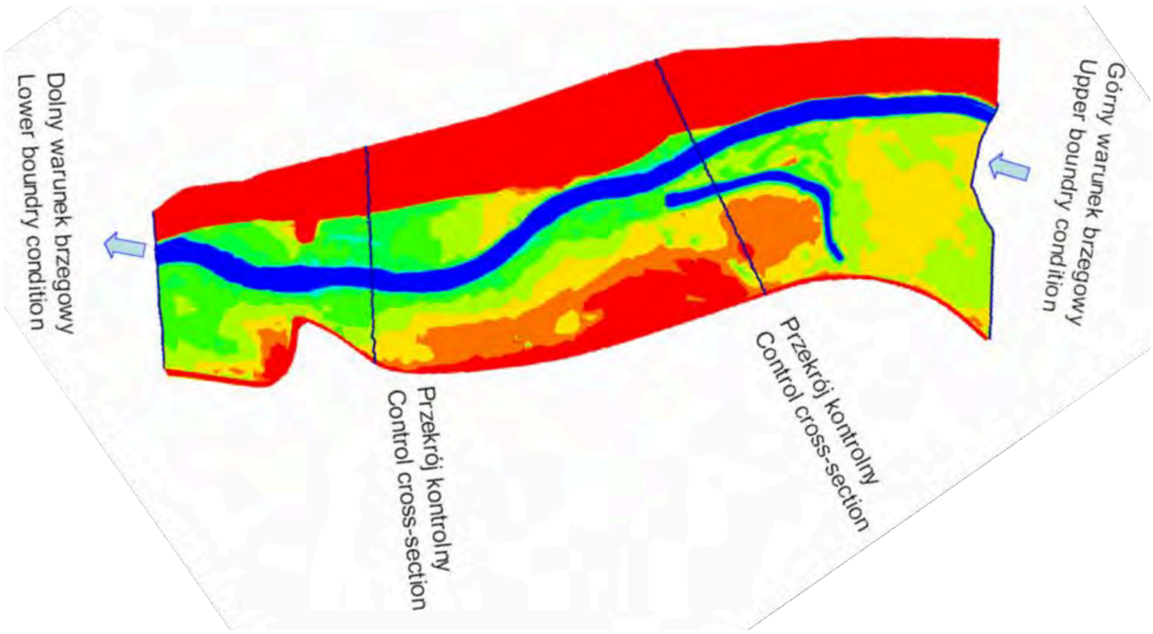

Figure 4: Location of boundary and control cross-sections

Flow measurements taken with a ADCP StreamPro probe in 2010 within the modelled section of the Warta made it possible to conduct a point comparison of field data with the results of simulations obtained from RISMO. Results of measurements made it possible to determine the accurate flow value and distribution of velocity at the cross-section, which may be used in procedures of 2D model verification and tare parameter specification. Based on analyses of in-situ measurements the geometry was determined for measurement cross-sections and distributions of velocity fields (Figs. 5 and 6). Cross-section 2 covers also an old marginal lake (Fig. 6).

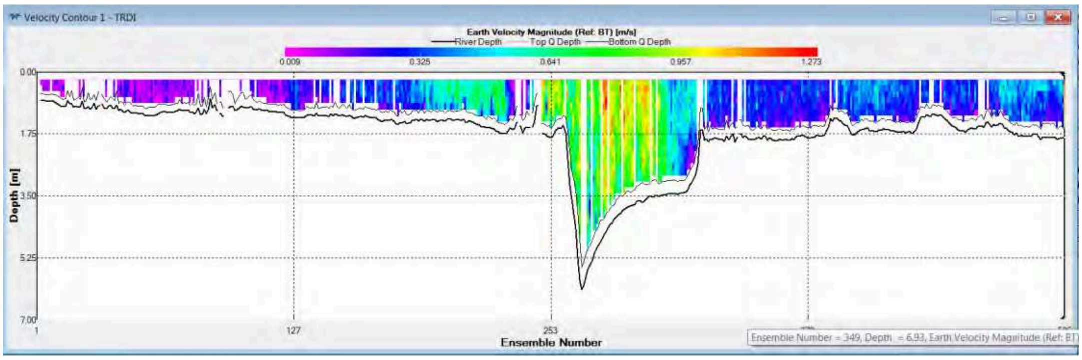

Figure 5: Measurement cross-section of a section at 353.5 km (cross-section 1) with velocity distribution

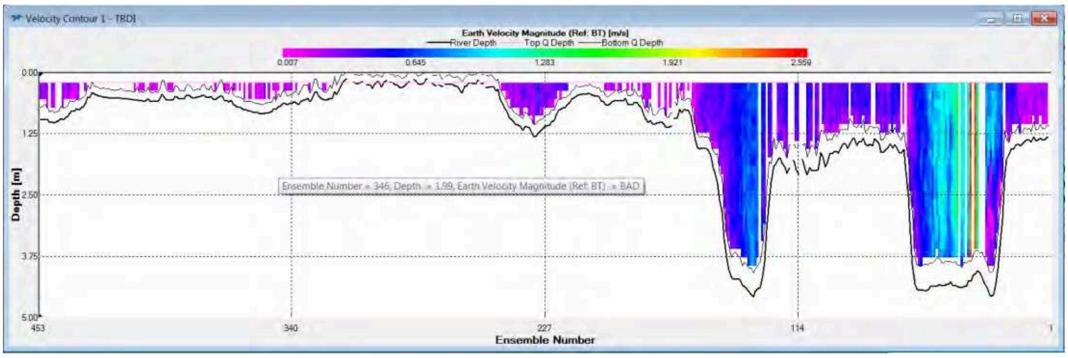

Figure 6: Measurement cross-section of a section at 354.28 km (cross-section 2) with velocity distribution

Velocity distributions are presented in Figs.7. We may observe high irregularity for measured velocities, which is related with errors appearing during measurements or a distortion of measurements connected with the vegetation cover in flood plains. For both control cross-sections the calculated and measured values of velocity fields have similar courses and the difference in maximum velocities does not exceed 0.08 m for cross-section 1 and 0.22 cm for cross-section 2. Both the course of velocity field and the slight difference in maximum velocities for control cross-section 1 indicates high consistency of measured and calculated values.

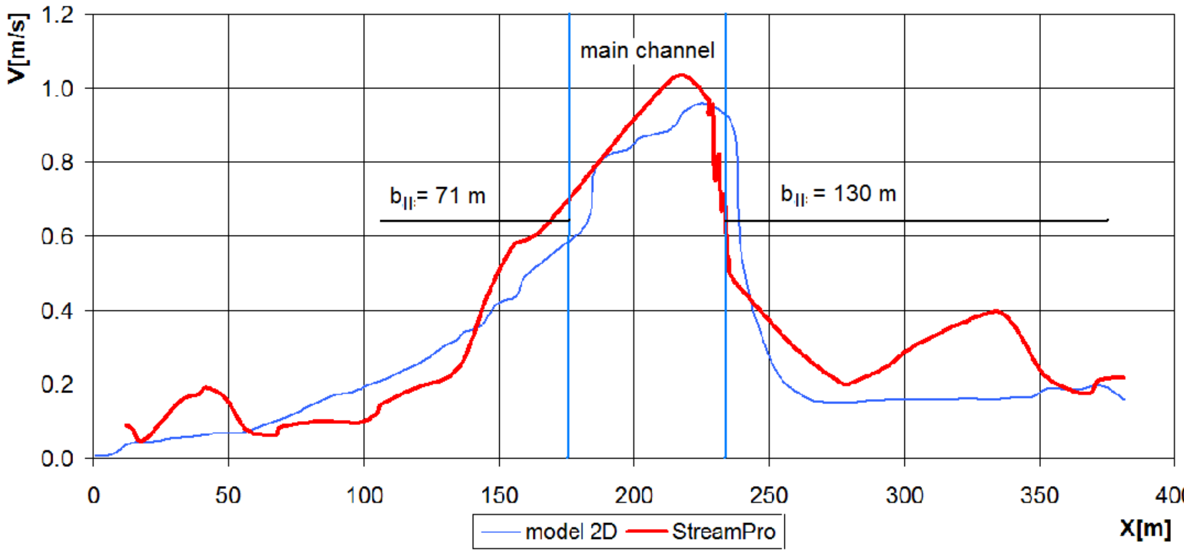

Figure 7: The range of th active flow zone at cross-section 1 with a comparison of velocity distribution measured with a StreamPro probe and calculated with a 2D model.

5 Determination of the range of active flow zone based on measurements

Data from measurements taken with an ADCP probe made it possible to determine the actual range of the active flow zone (Fig. 6). On this basis formula (1) was verified. It was assumed that the active zone of the cross-section comprises 95% total flow. The other 5% flow are symmetrically distributed on both sides of the channel. Thus zones need to be identified which take 2.5% total flow. Using the WinRiverII program boundary values of 2.5 % total flow were determined for the left and right banks.

For such assumptions the range of the active flow zone was calculated for the measurement cross-section 1 was 71 m for the left bank and 130 m for the right bank. These data are presented in Fig. 7, on which the distribution of measured velocities was also given. Much lower velocities on the left bank, which at a distance of 125 m from the embankment lines do not exceed 0.2 m/s cause a considerable reduction of the range of the active flow zone on that bank. Velocities on the right bank are over 0.2 m/s throughout its length, thus the range of the active zone is almost 2-fold greater than for the left bank. In case of cross-section 2 the range of the active zone was determined only for the left-bank flood plain. It was assumed that all 95% flow identifying the active flow zone takes place in the main river channel and on the left-bank flood plain.

For the obtained values parameter C_T was calculated for the assumed coefficients of resistance to motion and calculated values of hydraulic radius. These data are presented in table 1. The greatest value of parameter C_T, and this the smallest range of the active flow zone was calculated for the left-bank flood plain measurement cross-section 1. A slightly smaller value is assumed by that parameter for the right-bank flood plain of this cross-section, while the smallest is found for the left-bank measurement cross-section 2. In turn, this cross-section is characterized by the greatest hydraulic radius, which results from the incorporation of the old marginal lake in that cross-section, which considerably influences hydraulic parameters for the cross-section at the passage of the flood wave.

Table 1 Values of parameter C_T for measurement cross-sections

Measurement Cross-section	b_{ii}[m]	Roughness coefficient for flood plains ***n*** [$m^{-1/3}s$]	Hydraulic radius [m]	C_T [-]
1	71	0.038	1.25	2.13
1	130	0.038	1.64	1.81
2	175	0.038	1.44	1.26

6 Conclusions

In studies of the effect of wide natural flood plain valleys on the transformation of flood waves in 1D models it is essential to consider an accurate representation of the active flow zone. The basic parameter used in the determination of the active part of the cross-section is rubbing speed C_T, which depends on flow conditions in the main river channel and in flood plains. The authors proposed the application of a 2D model of the natural flood plain valley in the verification of the 1D model and the determination of parameter C_T. Additionally, based on the results of measurements from the flood in the Warta in 2010 they checked and verified assumptions constituting the basis for the determination of the active cross-section. Based on the measurements it was proposed to establish the active zone as an area covering 95% total flow. It is assumed that the other 5% flow is distributed symmetrically on both sides of the river channel. Much lower flow velocities in flood plains, frequently not exceeding 0.2 m/s, cause a considerable reduction of range of the active zone, which is limited to the main river channel and a part of the left- and right-bank zone.

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